8.—The vanadium-bearing magnetite gabbro* at Coates, Western Australia

by D. R. Hudson†

Manuscript received 21 February 1967; accepted 21 March 1967

Abstract

A recent investigation of the vanadium-bearing magnetite gabbro at Coates, Western Australia has made possible a study of unaltered rock samples from below the deep zone of lateritisation and kaolinisation. The association of oriented plagioclase tablets, abundant opaque oxides, cummingtonite and Na-hornblende is explained as an igneous differentiate from a gabbroic magma.

Analyses of the gabbro and its kaolinised equivalent indicate that vanadium has suffered only slight depletion during weathering. Laterites containing high concentrations of vanadium and titanium are derived from the gabbro by leaching and selective precipitation, but are of limited extent.

Vanadium is concentrated in the magnetite relative to the coexisting ilmenite, while manganese is preferentially accommodated in the ilmenite. The opaque oxides appear to be related to the titaniferous magnetite bodies occurring in central and northwestern Western Australia.

Introduction

Vanadium-bearing magnetite gabbros and associated laterites occur near Coates Siding, 45 miles by road east-north-east of Perth, Western Australia. The magnetite gabbro forms a prominent ridge extending northwest from Coates, with a probable minor extension 1.5 miles further to the north.

The gabbro has been extensively lateritised with almost complete destruction of the primary minerals. Original textural features, however, are generally well preserved and permit limited structural interpretation. Titanium-rich laterites occur high on the western flank of the ridge, while pisolitic laterites and lateritic soils occur on the eastern flank and on the western flank below the titanium-rich laterites. Granitic rocks outcrop to the east of the ridge and it is probable that the gabbro bears an intrusive relationship to them.

Early geological interest in the area centred on the possibility of exploiting the laterites as a source of iron for the nearby Wundowie charcoal-iron blast furnace (Connolly 1959). Several shallow prospecting pits were dug, both in the titanium-rich laterites and pisolitic laterites. The laterites, however, proved uneconomic to mine due to their sporadic distribution and undesirably high titanium content.

In 1961 interest was renewed in the laterites and the parent gabbro as a possible ore of vanadium. Mangore Australia Pty. Ltd., an Australian subsidiary of Union Carbide Corporation, carried out an extensive drilling and sampling programme, in the course of which a shaft was sunk to a depth of 101 feet in the centre of the lateritised magnetite gabbro. The shaft encountered unaltered gabbro 90 feet below the surface (Fig.1). A summary of the vanadium ores investigated by Mangore Australia Pty. Ltd. is given by Jones (1965).

* The modal composition departs markedly from the range normally covered by the term gabbro, but it has been so named in previous published work and there seems to be no appropriate alternative.

† University of Queensland, St. Lucia, Queensland.

Magnetite gabbro

Occurrence

The magnetite gabbro occurs as a steeply dipping NW-trending dyke, apparently intrusive into granite. Lateritised gabbro can be traced along strike for at least one mile with an average width of 300 feet. Compositional banding is pronounced, with variation from anorthositic bands to solid magnetite lenses. The latter appear to be relatively narrow, usually not wider than 6 inches, and rarely extend further than a few feet along strike. Abundant magnetite boulders, however, indicate that these lenses are widespread. Paucity of outcrop prevents a systematic study of compositional variation in the gabbro, but both the magnetite lenses and anorthosites are concentrated on the eastern wall of the dyke.

Despite lateritisation a strong palimpsest igneous lamination can be observed throughout the dyke. The foliation, developed by alignment of tabular plagioclase crystals, strikes parallel to the trend of the dyke and indicates a vertical or steep easterly dip. This dip is confirmed by the lenticular magnetite bodies.

Ground magnetometer traverses (Fig.1) give a high positive anomaly over the full width of the gabbro and confirm the limits of outcrop deduced from surface exposure.

General petrography

Although abundant lateritised magnetite gabbro can be observed at the surface, the only fresh material available for study comes from the bottom of the shaft. Here the rock is green-black in colour and is composed of coarse, tabular plagioclase crystals. Magnetite grains are interstitial to the plagioclase and are rimmed by dark green amphibole (Fig. 2). Chlorite veinlets, many of them carrying sulphides, are common.

Plagioclase (58.6 per cent., by volume) occurs in subhedral grains of average size 5 x 4 x 1.5 mm, which are tabular parallel to (010). Most grains show combined Carlsbad and albite twinning with rarer combined pericline twinning. A clouded appearance is given to the grains by minute exsolution rods. Patchy alteration to sericite and kaolin is common, and is particularly well developed in the cores of grains where it is sometimes associated with zoisite. Extinction angles X′ ∧ (010), measured normal to *a* are

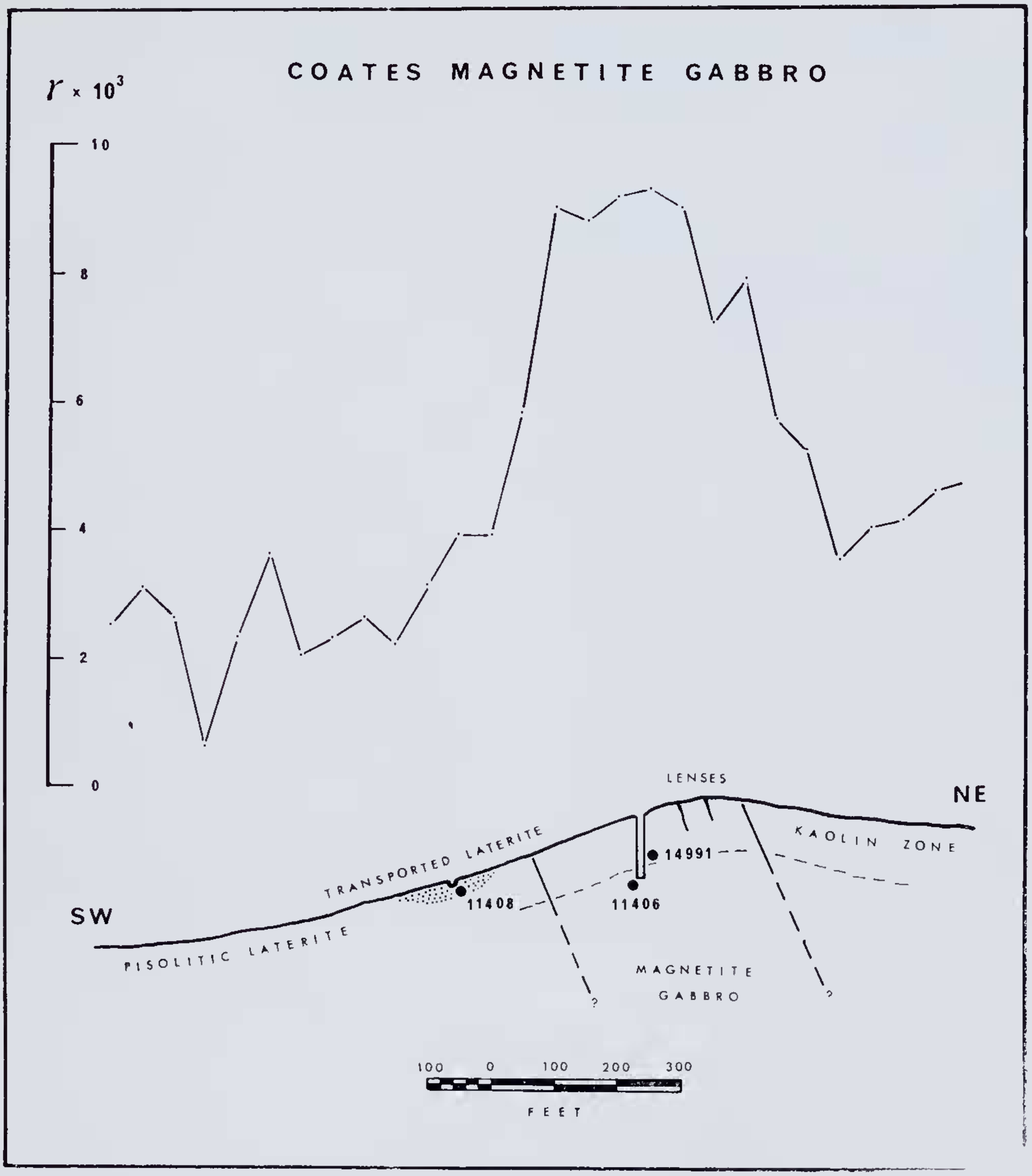

Figure 1.—Vertical section through Coates magnetite gabbro. (Numbers refer to specimens housed in the Department of Geology and Mineralogy, University of Queensland.)

29° ± 2°, indicating labradorite, An_{54}. Post crystallisation fractures and plagioclase-plagioclase and plagioclase-magnetite grain boundaries have been filled and replaced by prismatic to granular aggregates of Na-hornblende.

Na-hornblende (15.4 per cent.) occurs dominantly as aggregates growing normal to grain boundary interfaces. Larger subhedral grains, up to 2 mm in diameter have grown by replacement of cummingtonite. The mineral is strongly pleochroic, with X = pale yellow, Y = deep green and Z = blue-green. Refractive index δ = 1.687 ± 0.002.

Cummingtonite (1.6 per cent.) remains as colourless grains of average size 1.5 x 1 mm, showing partial or complete reaction to Na-hornblende. Abundant, drop-like exsolution particles (? magnetite) are arranged in rows parallel to (001) and (010). The mineral is optically positive with refractive index δ = 1.682 ± 0.002.

Biotite occurs as pale brown, pleochroic flakes intergrown with the Na-hornblende aggregates, while plumose chlorite fills veins cutting all other minerals.

Pyrite (0.3 per cent.) is associated with chlorite in small veinlets and also occurs as discrete granules throughout the rock.

Opaque oxides

The ore minerals are interstitial to the plagioclase tablets and form subcontinuous aggregates throughout the rock. Magnetite (20.1 per cent., by volume) is the dominant oxide and encloses smaller irregular grains of ilmenite (4.0 per

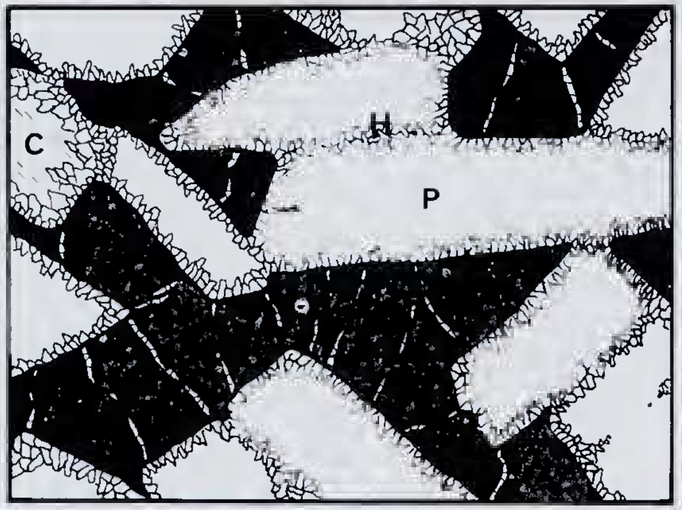

Figure 2.—Sketch of magnetite gabbro 11406, drawn from a thin-section. Width of field is 1 cm. Plagioclase (P), white; Na-hornblende (H), granular; cummingtonite (C); magnetite and ilmenite, black.

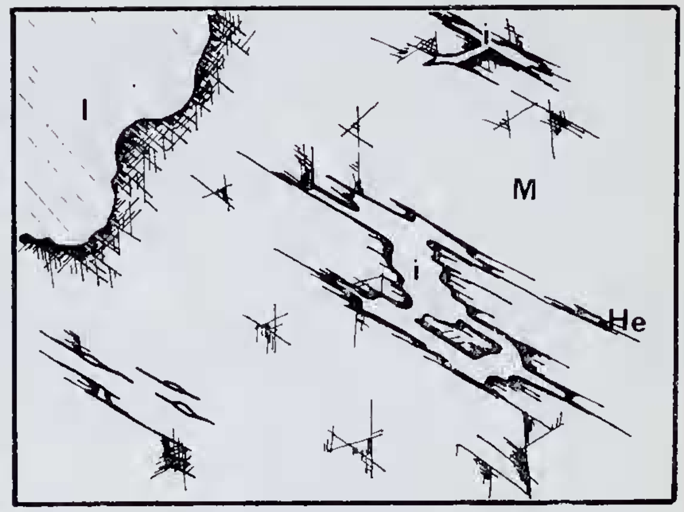

Figure 3.—Sketch of opaque oxides from gabbro 11406, drawn from a polished surface. Width of field is 1 mm. Magnetite (M), containing exsolved ilmenite (i); haematite (He), black; ilmenite (I).

cent.), most of which occur near the magnetite grain margin. The ilmenite grains rarely measure more than 1 mm in diameter and are usually much smaller. They are grey in colour and show marked anisotropism. Fine anisotropic lamellae (10 μ in length and 1 μ in width) occur parallel to (0001) and are probably exsolved haematite (Fig. 3). Vincent and Phillips (1954) record similar exsolution lamellae in ilmenites from the Skaergaard intrusion, but consider them to be dominantly magnetite.

Magnetite is grey in colour and isotropic. It is difficult to polish and almost always shows irregular pitting. Under low power, plates and lamellae of ilmenite, most of which are in the (111) planes of the magnetite, can be seen. The ilmenite has a much deeper purple tint than that occurring in discrete grains and contains no exsolved haematite. Under high power (x 400) further ilmenite rods can be seen in triangular intergrowths with magnetite. Haematite occurs rimming exsolved ilmenite and as fine octahedrally controlled textures in the magnetite (Fig. 3). Replacement of magnetite by haematite is common along ilmenite-magnetite grain boundaries and along fractures.

The solid magnetite lenses outcropping in the lateritised portion of the gabbro (11407) are extensively altered to haematite. Coarse ilmenite lamellae are visible under low power, but discrete ilmenite grains are rare or absent.

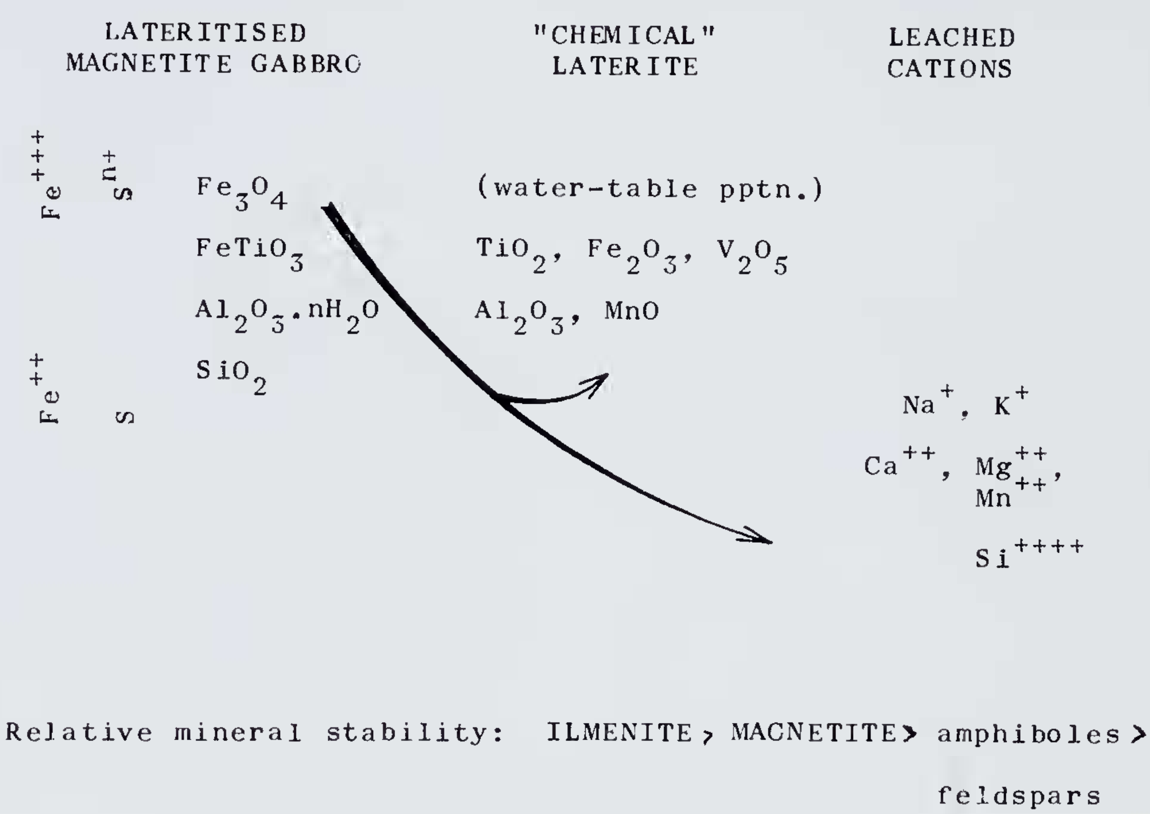

Figure 4.—Relationship between residual and transported laterites, Coates Siding.

TABLE 1

Chemical analyses of Coates magnetite gabbro
(Analyst: D. R. Hudson)

	ROCKS			MINERALS	
Weight per cent.	GABBRO 11406	KAOLINISED GABBRO 14991	LATERITE 11408	MAGNETITE 11406	ILMENITE 11406
SiO_2	30.07	23.05	0.16	0.38	
TiO_2	5.55	6.64	28.98	7.51	48.51
Al_2O_3	14.87	18.74	6.93	2.58	....
Fe_2O_3	19.08	27.67	51.63	60.07	6.40
Cr_2O_3	tr	tr	tr	nil	0.01
FeO	17.31	13.09	1.12	27.19	40.62
MnO	0.16	0.12	0.06	0.10	0.81
MgO	2.95	0.48	...	0.46	1.51
CaO	5.32	tr	....	0.02	0.22
Na_2O	1.58	0.18	....	.	....
K_2O	0.31	0.17			....
H_2O+	1.61	7.32	8.75	....	....
H_2O-	0.08	1.77	0.72	....	....
P_2O_5	0.34		....	.	.
V_2O_5	0.63	0.70	1.51	1.61	0.23
S	0.61		....	....	...
Total	100.47*	99.93	99.86	99.92	(98.31)
S.G.	3.40	2.0	3.1	5.03	4.62
Normative minerals			Cation proportions	Basis 32(0)	Basis 6(0)
Qtz.	2.22	20.55	Si	0.104	..
Or.	1.67	1.11	Al	0.898	....
Ab.	13.64	1.57	Ti	1.636	1.869
An.	24.79	....	Fe^{3+}	13.090	0.245
Cor.	2.80	18.25	V	0.313	0.009
Hyp.	12.60	1.20	Mg	0.192	0.113
Mag.	28.51	23.37	Fe^{2+}	6.600	1.735
Haem.	....	12.28	Mn	0.017	0.034
Ilm.	10.59	12.59	Ca	0.007	0.012
Pyr.	1.20	....	..	.	.
Ap.	0.67	....	...	....	.

* Includes: Cu = trace, Ni = trace.

X-ray powder diffraction data, determined using Co Kα radiation in an 11.483 cm diameter camera, gave a cubic cell dimension of a = 8.395 Å for magnetite 11406.

Chemistry of the opaque oxides

Analyses of magnetite and ilmenite appear in Table 1, together with their cation proportions. The marked excess of ferric iron in the magnetite is thought to be due to a combination of late crystallisation-oxidation and weathering. The effect of oxidation of magnetite during weathering can be seen in the magnetite lenses and ferruginised gabbro near the surface, where the mineral has been partially or completely replaced by haematite. Ilmenite, however, appears to be relatively unaltered, and the ferric iron occurs either as exsolved haematite or remains in solid solution.

Vanadium is concentrated in the magnetite relative to the coexisting ilmenite and has a similar distribution to that observed by Vincent and Phillips (1954) in the coexisting opaque oxides from the Skaergaard intrusion.

Manganese, on the other hand, is preferentially accommodated in the ilmenite lattice, as observed by Howie (1955) elsewhere. Buddington and Lindsley (1964) report an enrichment of Mn in coexisting ilmenite-magnetite from gabbroic rocks where Mn (magnetite)/Mn (ilmenite) = 0.65. The comparable distribution value for the Coates magnetite-ilmenite pair is 0.12. This ratio is identical with that found in Howie's Madras Series and also by the author in the granulites from central Australia. The difference between these two values seems too large to be due to temperature alone, and may reflect more complete exsolution of the ilmenite phase from magnetite in both the Coates gabbro and the metamorphic rocks.

Petrogenesis of the magnetite gabbro

The Coates gabbro is thought to have been intruded as a partially crystallised residiuum from a deep-seated gabbroic parent magma. Plagioclase tablets show an alignment parallel to the intrusive margins, consistent with them having been crystallised prior to emplacement. The opaque oxides, however, are interstitial and have crystallised after intrusion. Segregation of ilmenite granules within the magnetite precedes exsolution of haematite from ilmenite and ilmenite from magnetite. A temperature of formation of approximately 700° C, calculated from the analyses of magnetite and ilmenite according to the method of Buddington and Lindsley (1964), appears too low for a basic magmatic rock and may reflect removal of some coarse exsolved ilmenite from the magnetite during separation for analysis. The magnetite cell dimension indicates that almost all titanium has been exsolved and thus could be depleted during separation.

The small, solid magnetite lenses are explained as concentrations of interstitial liquids into tensional zones before complete solidification. Although the occurrence of these pods is restricted at Coates, it is conceivable that larger scale "filter-pressing" of the residual magnetite-rich liquid could give rise to magnetite bodies similar to those occurring in Western Australia at Roebourne and Gabanintha (Simpson 1952 p. 124).

Cummingtonite occurs as colourless grains altering to sodic hornblende, but is not considered to be the primary ferromagnesian mineral. A reaction from earlier formed hypersthene or olivine, as suggested by Stewart (1946), appears more likely. No evidence, other than pronounced exsolution of iron ore droplets (as observed by Stewart in similar cummingtonite), was found for this mechanism.

Final enrichment of the residual liquid in sodium has caused replacement of cummingtonite and reaction at plagioclase-magnetite interfaces to give Na-hornblende.

Lateritisation

Lateritic rocks of three types occur in the vicinity of the Coates magnetite gabbro: pisolitic laterites and lateritic soils, residual laterites (derived by *in situ* ferruginisation and kaolinisation of the magnetite gabbro) and chemically transported laterites. Of these only the residual and transported laterites can be directly associated with the gabbro and will be considered further.

Residual laterites

The magnetite gabbro has suffered extensive weathering to a depth of 80-90 feet which has destroyed all the primary minerals (except the opaque oxides) and yet left the original texture intact. Two distinct zones of weathering may be recognised. A surface zone of concentration, varying between 10 and 20 feet in thickness, in which deposition of ferric iron has produced a hard ferruginous crust, still containing primary ore minerals and relict texture. Magnetite in this zone shows extensive alteration to haematite.

Below the ferruginous crust, friable kaolinised gabbro extends downwards to the fresh rock. Rocks in this zone are pink, white, buff or grey in colour and commonly show mottling. Original plagioclase crystals are replaced by pink and white kaolin boxworks, but magnetite and ilmenite seem relatively stable in the weathering environment. Leaching of material has occurred mainly from this zone and is indicated by the extremely low density of the rock. Depletion of Ca, Mg, Na, K and to a lesser extent Si during the weathering is most marked. A comparison between the normative minerals from the unaltered gabbro and the kaolinised gabbro gives an indication of the "minerals" that have been destroyed during the weathering and leaching processes (Table 1). The stability of ilmenite and the gradual oxidation of magnetite to haematite can also be seen. No sulphide minerals remain in the zone of weathering and oxidation. An attempt by Muskett *et al.* (1965) to establish a process to "up-grade" these laterites proved only partially successful.

Transported laterites

Limited exposures of dark chocolate-brown to purple-brown laterites occur on the western flank of the gabbro. These rocks have a porous structure with cavities 2 to 10 mm in diameter. A vitreous to submetallic rim of oxides commonly surrounds these holes. The thickness of these laterites is not known, but they are at least 10 feet and probably not more than 25 feet thick.

The composition is unusual, with extremely high TiO_2, Fe_2O_3, Al_2O_3 and an enrichment of V_2O_5 relative to the magnetite gabbro (Table 1). The cations of these oxides would be precipitated from an alkaline aqueous solution, while Na^+, K^+, Ca^{++}, Mg^{++}, and to a lesser extent Mn^{++}, would remain in solution. Both the physical properties and composition of the laterites indicate that some chemical transfer and selective precipitation has been operative, and their formation has probably been controlled by an old water table (Fig. 4).

Conclusions

The Coates vanadium-bearing gabbro occurs as a sheet-like igneous instrusion. Strong flow-layering indicates that plagioclase was largely crystallised before intrusion, whereas interstitial crystallisation of magnetite and ilmenite occurred *in situ*. Late magmatic alteration of magnetite and cummingtonite has formed Na-hornblende.

The lenticular vanadium-bearing titaniferous magnetite bodies extending from Gabanintha to Barrambie, and also outcropping near Roebourne are thought to represent a similar igneous differentiation, from a gabbroic parent magma, to that suggested for the Coates gabbro, with the exception that only the non-crystalline (plagioclase deficient) portion has been mobilised and intruded.

Acknowledgements

The author wishes to thank the directors of the Union Carbide Ore Corporation for permission to publish some of the data collected while employed by Mangore Australia Pty. Ltd. Mr. A. S. Bagley prepared the X-ray powder diffraction photograph of magnetite.

References

Buddington, A. F., and Lindsley, D. H. (1964).—Iron-titanium oxide minerals and synthetic equivalents. *J. Petrol.* 5 (no. 2): 310-355.

Connolly, R. R. (1959).—Iron ores in Western Australia. *Geol. Surv. W. Aust.*, Mineral Resources Bull. 7.

Howie, R. A. (1955).—The geochemistry of the charnockitic series of Madras, India. *Trans. Roy Soc. Edin.* 62: 725-768.

Jones, W. R. (1965).—Vanadium deposits of Western Australia. *Eighth Comm. Min. Met. Congr.* Vol. 1, Geology of Australian Ore Deposits: 154-155.

Muskett, G. H., Tasker, E., and Hobson, R. A. (1965).—Concentration of a low-grade vanadiferous iron ore from Coates, near Wundowie, Western Australia. *C.S.I.R.O. and W.A. School of Mines, Kalgoorlie.* Ore dressing Investigation, Report 735.

Simpson, E. S. (1952).—"Minerals of Western Australia". Volume 3. Govt. Printer, Perth.

Stewart, F. H. (1946).—The gabbroic complex of Belhelvie in Aberdeenshire. *Quart. Journ. Geol. Soc.* 102: 465-498.

Vincent, E. A., and Phillips, R. (1954).—Iron-titanum oxide minerals in layered gabbros of the Skaergaard intrusion, East Greenland. Part 1: chemistry and ore-microscopy. *Geochim et Cosmochim. Acta* 6 (No. 1): 1-26.